

EJECTION OF FRAGMENTS IN SUPERNOVA EXPLOSIONS

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Recent observations by the ROSAT X-ray satellite of the Vela supernova remnant¹ have revealed, in addition to the previously identified compact nebula², a nearly circular emitting region with a radius of about 4 degrees. The Vela pulsar is slightly off the center of this circular region, consistent with its measured proper motion³ of about 100 km s^{-1} and an age of about 10^4 yr . The emitting region is bounded by the main supernova shock. Just outside the shock, the X-ray image reveals several well-defined V-shaped features extending radially outwards¹. These features are most likely wakes produced by objects moving supersonically through the outside medium. The shapes and orientations of the wakes suggest that these objects have been ejected from the center of the supernova explosion. Their present positions indicate that they have been moving with a mean velocity of a few thousand km s^{-1} . We show that pre-existing objects, such as planets in orbit around the progenitor star, could not have been accelerated to sufficiently high velocities or would have been destroyed. Instead, we propose that the observed objects are fragments ejected during the formation of the neutron star. Fragmentation during gravitational collapse is a natural consequence of both convective⁴ and rotational⁵ instabilities.

The X-ray emitting wakes observed by ROSAT appear in the North, East and West of the Vela supernova remnant and are stretched radially outwards¹. Their

angular distance from the center is about 4° , giving a mean velocity $v_f = 2.8 \times 10^3 d_4 \tau_4^{-1} \text{ km s}^{-1}$, where $400 d_4 \text{ pc}$ is the distance to the remnant and $10^4 \tau_4 \text{ yr}$ is its age³. The initial ejection velocity must clearly have been $> v_f$. For the brighter of the three features, the ROSAT PSPC countrate is about 0.25 s^{-1} and the emitting area is about 32 arcmin^2 , giving an X-ray luminosity $L_x \sim 10^{34} d_4^2 \text{ erg s}^{-1}$ (J. Trümper, personal communication). This implies a total radiated energy of $\sim 3 \times 10^{45} d_4^2 \tau_4 \text{ erg}$ over the lifetime of the remnant. If a moving fragment were to supply this energy while decelerating from the above v_f , its mass should be $\gtrsim 10^{-4} M_\odot$.

We can immediately rule out the possibility that the fragments are pre-existing objects (e.g. planets) that were accelerated by the explosion. The progenitor star was most likely a supergiant of radius $R_p > 10^{13} \text{ cm}$. The total energy imparted to the ejected stellar envelope in a supernova explosion is $E_s \sim 10^{51} \text{ erg}$. This energy includes both thermal and bulk velocity components. The initial velocity of the shocked fluid is $v_s \sim 10^4 \text{ km s}^{-1}$. Thus, the total momentum flowing out is $< 2E_s/v_s \sim 2 \times 10^{42} \text{ g cm s}^{-1}$. The fraction of this momentum outflow that can be intercepted by an object of radius R_f outside the progenitor is $< (R_f/R_p)^2$. Objects orbiting inside the progenitor are dragged to the center and destroyed on a very short timescale⁶ $\tau_d \sim 10^3 \text{ s}$. The ejection velocity for an external object with mass M_f and mean density ρ_f is $v_f < [2E_s/(v_s M_f)](R_f/R_p)^2$, giving

$$v_f < 6 \text{ km s}^{-1} \left(\frac{M_f}{10^{-3} M_\odot} \right)^{-1/3} \left(\frac{\rho_f}{1 \text{ g cm}^{-3}} \right)^{-2/3} \left(\frac{R_p}{10^{13} \text{ cm}} \right)^{-2}. \quad (1)$$

For planets this upper limit is at least three orders of magnitude smaller than the value of v_f deduced from the observations. Even if the planets could somehow survive inside the supergiant envelope, the explosion would destroy them. Indeed, disruption occurs whenever the nonuniform pressure forces exerted by the ejected gas exceed a significant fraction ~ 0.1 of the internal gravitational force that keeps the planet bound. A planet at a distance r away from the center must be accelerated to its ejection velocity $> v_f$

in a time r/v_s , and the condition $v_f/(r/v_s) < 0.1GM_f/R_f^2$ translates to the lower bound

$$r > 10^{15} \text{ cm} \left(\frac{M_f}{10^{-3} M_\odot} \right)^{-1/3} \left(\frac{\rho_f}{1 \text{ g cm}^{-3}} \right)^{-2/3} \left(\frac{v_f}{2 \times 10^3 \text{ km s}^{-1}} \right). \quad (2)$$

Expressions (1) and (2) show clearly that planets cannot be accelerated to the required velocity without being totally disrupted.

Instead we propose that the observed wakes are associated with fragments that were ejected from inside the progenitor core during an asymmetric gravitational collapse. During the acceleration phase, the density inside the fragments was $\rho_i \sim 10^{10-15} \text{ g cm}^{-3}$, high enough for the fragments to avoid disruption. Direct evidence for asymmetric core collapse is provided by the large observed proper motions of young pulsars⁷. Two specific mechanisms can result in the formation of small fragments. Rotationally-induced instabilities during gravitational collapse⁵ can lead to the development of either an axisymmetric, self-gravitating disk⁸, or an ellipsoidal deformation, which then leads to mass shedding through outgoing spiral arms^{9,10}. The spiral arms can later fragment through a sausage instability, leaving small compact objects orbiting the central neutron star core¹¹. The fragments in this case would be initially at close to nuclear density, $\rho_i \sim 10^{14} \text{ g cm}^{-3}$, and ejected from $r_i \sim 10^{1-2} \text{ km}$. They would be formed just outside the radius where the bounce shock forms initially, and so they could be shock-accelerated and ejected before the shock stalls¹². Alternatively, Rayleigh-Taylor (convective) instabilities in the outer iron core⁴ can lead to small blobs of overdense material forming behind the shock front. These overdense blobs could be accelerated by absorbing a small fraction of the neutrino flux, i.e., through the same mechanism that is now commonly thought to re-energize the stalled shock and power the ejection of the stellar envelope^{4,12}. In this case the initial density is lower, $\rho_i \sim 10^{10} \text{ g cm}^{-3}$, and the ejection is from $r_i \sim 10^{2-3} \text{ km}$.

In response to the release of nuclear energy in their interior, fragments that are too small may disintegrate. Consider a fragment made of hot ($T \gtrsim 1$ MeV), highly neutronized material. As the fragment expands, nucleons recombine quickly into nuclei. At relatively late times the energy release is dominated by β -decays¹³. The maximum amount of nuclear energy released is about 8 MeV per nucleon if all the matter transforms into iron. The actual energy which gets thermalized inside the fragment is likely to be considerably smaller, because part of the nuclear energy is carried away by neutrinos, and because the fragment may not form out of highly neutronized matter. Ignoring degeneracy pressure, a necessary condition for a fragment to remain gravitationally bound is that the thermalized nuclear energy be smaller than the gravitational binding energy per baryon,

$$T < E_{\text{grav}} = 4 \text{ MeV} \left(\frac{M_f}{10^{-2} M_{\odot}} \right)^{2/3} \left(\frac{\rho_i}{10^{14} \text{ g cm}^{-3}} \right)^{1/3}. \quad (8)$$

We therefore obtain a conservative estimate of $\sim 0.01 M_{\odot}$ for the minimum mass of a fragment that would not disintegrate as a result of nuclear energy release.

Even if it can sustain the nuclear energy release, a fragment could still be unbound if it is produced with an initial temperature much larger than the virial temperature. Just like a nascent neutron star, a newly formed hot fragment can cool rapidly by neutrino emission, to which it is optically thin. When the neutrino cooling time becomes comparable to the hydrodynamic time, the fragment begins expanding and may become unbound if its temperature is still too high. The neutrino cooling time due to pair annihilation is¹⁴ $10^{-4} \text{ s} (T/10 \text{ MeV})^{-5}$. If we take the sound speed to be $\sim 0.1c$ and the initial fragment size to be ~ 1 km, then the hydrodynamic expansion time is $\sim 3 \times 10^{-5} \text{ s}$. This becomes comparable to the neutrino cooling time at $T = T_c \approx 12 \text{ MeV}$. The exact value of the sound speed is not important since $T_c \propto c_s^{1/5}$. Using equation (8) we conclude that for initially hot fragments, the mass must be

$\gtrsim 0.01M_\odot$ to avoid disintegration. This estimate turns out to be comparable to that obtained above by considering only the nuclear energy release.

As the fragments move away from the center of the explosion on ballistic orbits, they expand and eventually settle into a gravitational equilibrium with a density $\sim 1 \text{ g cm}^{-3}$. However, they could remain hot for a time $\gg 10^4 \text{ yr}$ because of their large initial thermal heat content as well as the energy release from radioactive nuclei in their interiors. An evaporation process should result. We write the evaporation rate in terms of the mass flux at the surface,

$$-\dot{M}_f = 4\pi\rho_e R_f^2 v_e, \quad (10)$$

where ρ_e is the density of the wind at ejection and where the ejection speed v_e must be larger than the escape velocity from the surface of the fragment,

$$v_e \gtrsim v_{esc} \equiv 1.3 \times 10^2 \text{ km s}^{-1} \left(\frac{M_f}{10^{-2}M_\odot} \right)^{1/3} \left(\frac{\rho_f}{1 \text{ g cm}^{-3}} \right)^{1/6}. \quad (11)$$

From mass conservation the density in the terminal velocity outflow is

$$\rho(r) \approx \frac{\rho_e R_f^2}{r^2}. \quad (12)$$

We can estimate the radius r_d where the outflow will be deflected by the ram pressure of the external medium from the condition

$$\rho(v_e^2 - v_{esc}^2) = \rho_{ext} v_f^2, \quad (13)$$

where $\rho_{ext} \sim 10^{-24} \text{ g cm}^{-3}$ is the ambient interstellar density. Taking $(v_e^2 - v_{esc}^2) \sim v_{esc}^2$, we find

$$r_d \approx \left(\frac{|\dot{M}_f| v_{esc}}{4\pi\rho_{ext} v_f^2} \right)^{1/2} \sim 4 \times 10^{16} \text{ cm} \left(\frac{\dot{M}_f}{\dot{M}_{max}} \right)^{1/2} \left(\frac{v_f}{2 \times 10^3 \text{ km s}^{-1}} \right)^{-1}, \quad (14)$$

where $-\dot{M}_{max} \equiv 10^{-6} M_\odot \text{ yr}^{-1}$ is the maximum evaporation rate allowed for a fragment of mass $10^{-2} M_\odot$ over the current pulsar lifetime. This radius r_d gives the effective

cross-section for estimating the drag force $F_d \sim \rho_{ext} v_f^2 \times (\pi r_d^2)$. The corresponding energy dissipation rate $F_d v_f$ yields a luminosity,

$$L_x \approx \pi \rho_{ext} v_f^3 r_d^2 \sim 4 \times 10^{34} \text{ erg s}^{-1} \left(\frac{v_f}{2 \times 10^3 \text{ km s}^{-1}} \right) \left(\frac{\dot{M}_f}{\dot{M}_{max}} \right). \quad (15)$$

This crude estimate comes very close to the observed X-ray luminosity determined from the ROSAT observation. Most of the energy is expected to be released by thermal bremsstrahlung in X-rays since the post-shock temperature of the gas is high. In fact, the Vela supernova may have ejected additional high velocity fragments. However, fragments with $|\dot{M}_f| \ll |\dot{M}_{max}|$ are too faint to be detectable by ROSAT, while those with a much higher evaporation rate would have disappeared by now.

To power an evaporation rate close to \dot{M}_{max} requires little energy deposition at the surface of a fragment, namely $\sim 100 \text{ eV}$ per baryon. This energy can be easily supplied over 10^4 years by short-lived radioactivity or by the initial heat content of the fragment. In order to maintain an appreciable evaporation rate, the temperature at the surface of the fragment must be $\sim 1/3$ of the escape temperature¹⁵,

$$T_s \approx 3 \times 10^5 \text{ K} \left(\frac{M_f}{10^{-2} M_\odot} \right)^{2/3} \left(\frac{\rho_f}{1 \text{ g cm}^{-3}} \right)^{1/3}. \quad (16)$$

The material in the evaporative outflow is initially fully ionized. As the surface material expands and rarefies to become part of the supersonic wind, it cools adiabatically with $T \propto \rho^{2/3}$. The gas starts to recombine within a distance $\sim R_f$ and eventually reaches a sufficiently low ionization level, so that the outflow becomes optically-thin, at a temperature $T_{ph} \approx 5000 \text{ K}$ around $r_{ph} \sim 3R_f$. The emerging optical luminosity from the wind photosphere is then,

$$L_{opt} \approx 4\pi r_{ph}^2 \sigma T_{ph}^4 \sim 10^{33} \text{ erg s}^{-1} \left(\frac{r_{ph}}{3R_f} \right)^2 \left(\frac{M_f}{10^{-2} M_\odot} \right)^{2/3} \left(\frac{\rho_f}{1 \text{ g cm}^{-3}} \right)^{-2/3} \quad (17)$$

where σ is the Stefan-Boltzmann constant. This estimate is highly uncertain because of the unknown contribution of heavy elements and molecular absorption to the opacity

of the wind. Nevertheless, it shows that the optical luminosity of the fragments may be detectable. It should therefore be useful to search for optical emission near the leading edges of the X-ray emitting wakes.

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